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Conceptual Systematic Stability Analysis of Power Electronics based Power Systems

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***Abstract*—System stability is a great concern in power electronics based power systems due to the interactions caused by the wide timescale control dynamics of power converters. Inspired by extensive research works in the small signal stability analysis, this paper presents a systematic stability analysis framework, aiming to provide a holistic approach, identifying the instability roots and predicting stability region. The proposed approach is both for stability-oriented design and stable operation evaluation, aiding for a more reliable and secure power system. A case study is performed for a grid connected multi-converter system as a practical application with simulation and experimental verifications.**

I. Introduction

Recent decades have seen a wide utilization of power electronic converters in the electrical power systems, for their wide applications in the integration of renewable energy sources (Photovoltaics and wind turbines), high voltage DC transmission (HVDC) and flexible AC transmission system (FACTS), transportation electrification systems, etc [1]. Power electronic converters enable the full controllability as well as improved performance and efficiency of the modern power systems [2]. However, the fast dynamic and low inertia also cause challenges in order to obtain stable operation [3].

Power system stability is a significant issue since the 19th century. In conventional power systems, control and dynamics are slow, usually falling far below the fundamental frequency and the electro-mechanical stability issue in synchronous generators is the major concern [4]. However, in the modern power electronics based power systems, the stability issues are different with the electro-mechanical stability issue in the conventional power systems. The wide timescale control dynamics of power converters can cause interactions with both electromechanical dynamics in electrical machines and electromagnetic transients in power networks, resulting in wide timescale stability issues, e.g. low frequency oscillations driven by the outer controller and PLLs, and high frequency oscillations driven by mutual interactions between the fast inner control loops of the grid connected converters [3], [5]. Moreover, the high penetration of renewable sources also reduce system inertia and introduce power fluctuations [6]. Another significant concern is the high complexity of the power electronic based power system caused by the large number of power electronic converters with dedicated control loops, which complicates the system level modeling and analysis, and also increases difficulties in locating the instability roots [7]. Therefore, it is of significant importance to perform accurate stability analysis for design and operation of power electronics based power systems.

Many research works have been conducted for the small signal stability analysis of power systems, either using eigenvalue method or impedance-based method. In eigenvalue method, system state space model is derived and linearized at the operating point, then system stability is assessed by examining eigenvalues of the system state space matrix. The eigenvalue method has been widely applied for stability analysis of grid connected PV systems [6], inverter based microgrid [8], wind farms [9], HVDC system [10], etc. The advantages of eigenvalue method are the identification of oscillation mode and participation factors of system variables; the drawback of the eigenvalue approach is that it needs to know the full system information which may be kept privacy by different vendors [11]. In impedance-based approach, a system is divided as source equivalent and load equivalent, and system stability can be determined by the impedance ratio of load and source with Nyquist criterion [11]. The impedance based method has been widely used in cascaded converter systems [12], grid connected converter systems [13] and wind power systems [14]. The advantage of impedance-based method is its black box feature, where the detailed knowledge of the parameters and properties of the system is not required as long as measurements can be obtained [11]. The impedance can be extracted based on the measured signals with frequency scanning [15]. This also provides a promising technique for the online stability assessment. Drawbacks of the impedance method include the conservative results and unable to identify the oscillation modes and participation factors. Considering different advantages and weaknesses of eigenvalue method and impedance based method, they are suitable for analyzing different stability phenomena.

Considering the significance of small signal stability in power electronics based power systems and inspired by the

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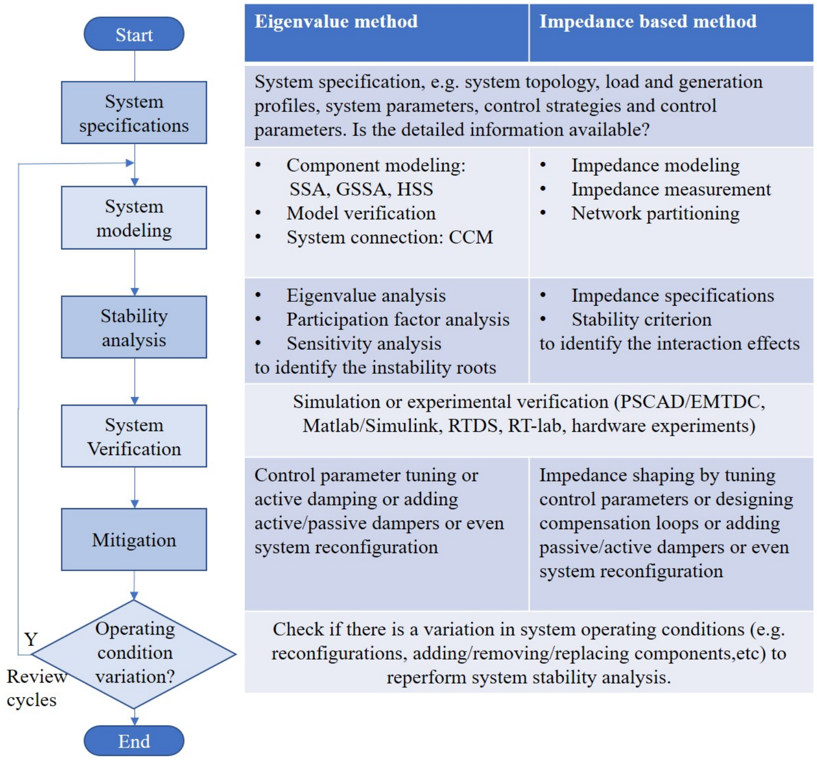

Fig. 1. The proposed systematic analysis framework.

existing research works in eigenvalue method and impedance-based method, this paper proposes a systematic stability analysis framework, aiming to provide a guideline for overall system analysis, including the selection of stability analysis tools given the available system information, system modeling, prediction of system stability region, identification of the critical points and instability roots, system verification and mitigation. The proposed approach is both for stability-oriented design and real-time stable operation, aiding for a more reliable and secure power system. A case study for a grid connected multi-converter system is conducted in both PSCAD simulation and laboratory experiment as a practical demonstration.

This paper is organized as follows: Section II presents the proposed systematic stability analysis framework. A case study is conducted with simulation and experimental verifications in Section III. Conclusions are drawn in Section IV.

II. The Proposed Systematic Stability Analysis Framework

For the design and operation of power electronics based power system, when oscillation or even unstable phenomena appear, it is significant to perform stability analysis to ensure the enough stability margin, identify the instability roots and provide mitigation strategies to avoid the problems. Fig. 1 illustrates the proposed systematic analysis framework.

To begin with, system specifications are collected to design a stable power electronics power system, including the topology, load and generation profiles, system parameters, control strategies and control parameters, etc. Then a proper analysis tool will be selected for stability analysis considering the available system information and the stability issues to be studied.

If the eigenvalue method is selected, the systematic stability analysis procedure is shown in the left half part of the table in Fig. 1. Eigenvalue method requires detailed state-space modeling of the system. Based on the different accuracy requirements, state-space averaging (SSA) method [7], generalized state space averaging (GSSA) method [10] and harmonic state-space (HSS) method [5] can be applied for modeling of power converters. The state-space models should be verified by simulations of switched models. To form the overall system small signal state-space model, the component connection method (CCM) is employed for model connection, which provides a modular and scalable solution for the large scale power electronics based power system integration [16]. Next, system stability is analyzed by evaluating eigenvalues of system matrix with participation factor analysis and sensitivity analysis. The eigenvalues indicate different oscillation modes and damping characteristics. The participation factor analysis calculates the contribution of each state to a certain mode, which can identify the states that have dominant effects on the dominant eigenvalues. Parameters associated with the dominant states (e.g. line impedance, filters, controller gain, delay time, PLL bandwidth, etc.) will be investigated through sensitivity analysis. Then the ranges of the operating points and system parameters for stable operation can be obtained.

The time-domain simulations or experiments for stable and unstable conditions will be performed to validate the analytical results. Based on stability analysis results, parameter tuning or active damping can be performed, or active/passive dampers can be added, or even doing reconfiguration for the mitigation of the critical parts to enhance stability. Finally the loop will check if there are variations in system operating conditions (e.g. reconfigurations, adding/removing/replacing components, etc) for a reperform of the system stability analysis procedure from the beginning.

If the impedance based approach is selected, the procedure is illustrated in the right half part of the table in Fig. 1. In the impedance-based approach, a system is divided as a source equivalent and a load equivalent. Impedance models are derived based on the transfer functions from current to voltage in a small signal sense. For AC systems, impedance models can be built either in dq domain or sequence domain [15]. If the detailed information is not available, impedance measurement techniques can be utilized to extract the source impedance and load impedance through frequency scanning [12][13]. Impedance models can also be verified through frequency scanning of simulation or experiments. Then a proper partitioning interface should be selected for stability analysis. The stability criterion (e.g. Nyquist, Gain Margin and Phase Margin, etc.) can be utilized to analyze system stability with the variation of operating conditions and parameters under study [11]. Impedance specifications are evaluated to analyze the interaction effects at different frequency ranges. Simulation or experimental verification will be conducted for the validation of analytical results. Based on the impedance specification and stability results, impedance can be reshaped by the mitigation strategies to meet the stability criterion. Then the loop will check the operating condition if it is necessary to reperform the stability analysis.

Based on the analysis procedure and results from the two methods, the selection criteria of the eigenvalue method and impedance based method is obtained as Table I. The eigenvalue method has advantages in identifying oscillation modes and participation factor of system variables and it is preferred for comprehensive systematic analysis; the impedance based method has black-box feature, which makes it a powerful technique when the system details are unavailable or for online stability assessment; the impedance based method is also suitable for analyzing interactions of subsystems and the design of converters.

TABLE I
THE SELECTION CRITERIA OF SMALL SIGNAL ANALYSIS TOOLS

Stability analysis requirements	Eigenvalue method	-
Identification of oscillation modes	√	-
Participation factor of state variables	√	-
Black box (privacy)	-	√
Converter design oriented analysis	-	√
Interaction effects of two subsystems	-	√

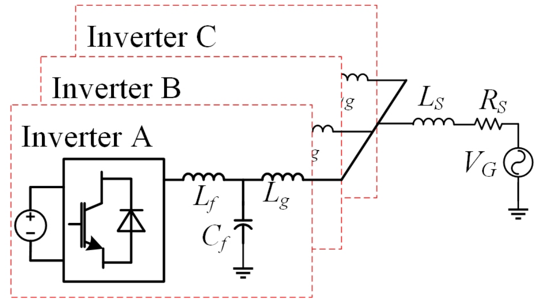

Fig. 2. The grid connected three-inverter system system under study.

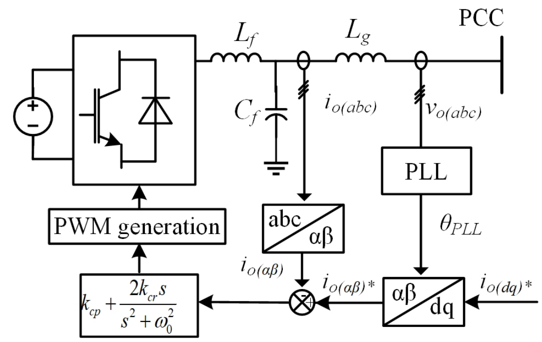

Fig. 3. Control implementation for each grid connected inverter.

III. CASE STUDY

To demonstrate the proposed stability analysis framework, the grid connected three-inverter system in Fig. 2 is studied in Matlab/Simulink and laboratory experimental setup, which is based on the Cigre LV benchmark system [17]. The inverters are in current controlled mode with PR controllers in the stationary frame (only current loop is considered) [18]. System parameters and control parameters are in Table II. Both the eigenvalue method and impedance based method procedures in Fig. 1 are conducted for systematic stability analysis of the grid connected three-inverter system.

A. Eigenvalue method

The stability analysis using eigenvalue method is performed by following the framework in Fig. 1 as follows:

TABLE II
SYSTEM PARAMETERS

Inverters		Inverter A	Inverter B	Inverter C
Nominal frequency (Hz)		50		
Sampling frequency (kHz)		20		
Filter values	L_f(mH)	3	2	1.5
	C_f(μF)	3	5	5
	L_g(mH)	3	2	1.5
Parasitic values	r_{Lf}(Ω)	0.0628	0.0471	0.0471
	r_{Cf}(Ω)	0.1061	0.0637	0.0637
	r_{Lg}(Ω)	0.0942	0.0628	0.0471
Controller gain	k_{cr}	20	12	12
	k_{cr}	600	600	600

1) System modeling: Modeling of power converters is a key issue in system modeling due to their switching dynamics and time-varying effect. Here the commonly used SSA method is applied. Based on the system topology and control implementation, the state space model of Inverter i (i=A, B and C) and grid side are derived as

$$\begin{cases} \frac{di_{Lfd,i}}{dt} = -\frac{r_{Lf,i}}{L_{f,i}} i_{Lfd,i} + \omega i_{Lfq,i} + \frac{1}{L_{f,i}} v_{ind,i} - \frac{1}{L_{f,i}} v_{Cfd,i} \\ \frac{di_{Lfq,i}}{dt} = -\frac{r_{Lf,i}}{L_{f,i}} i_{Lfq,i} - \omega i_{Lfd,i} + \frac{1}{L_{f,i}} v_{inq,i} - \frac{1}{L_{f,i}} v_{Cfq,i} \\ \frac{dv_{Cfd,i}}{dt} = \frac{1}{C_{f,i}} i_{Lfd,i} + \omega v_{Cfq,i} - \frac{1}{C_{f,i}} i_{Lgd,i} \\ \frac{dv_{Cfq,i}}{dt} = \frac{1}{C_{f,i}} i_{Lfq,i} - \omega v_{Cfd,i} - \frac{1}{C_{f,i}} i_{Lgq,i} \\ \frac{di_{Lgd,i}}{dt} = -\frac{r_{Lg,i}}{L_{g,i}} i_{Lgd,i} + \omega i_{Lgq,i} + \frac{1}{L_{g,i}} v_{Cfd,i} - \frac{1}{L_{g,i}} v_{pccd,i} \\ \frac{di_{Lgq,i}}{dt} = -\frac{r_{Lg,i}}{L_{g,i}} i_{Lgq,i} - \omega i_{Lgd,i} + \frac{1}{L_{g,i}} v_{Cfq,i} - \frac{1}{L_{g,i}} v_{pccq,i} \\ \frac{dx_{1d,i}}{dt} = i^*_{Lgd,i} - i_{Lgd,i} \\ \frac{dx_{1q,i}}{dt} = i^*_{Lgq,i} - i_{Lgq,i} \\ v_{ind,i} = k_{cp,i}(i^*_{Lgd,i} - i_{Lgd,i}) + k_{cr,i} X_{1d,i} \\ v_{inq,i} = k_{cp,i}(i^*_{Lgq,i} - i_{Lgq,i}) + k_{cr,i} X_{1q,i} \end{cases} \tag{1}$$

$$\begin{cases} \frac{di_{Gd}}{dt} = -\frac{r_S}{L_S} i_{Gd} + \omega i_{Gq} + \frac{1}{L_S} v_{Gd} - \frac{1}{L_S} v_{pccd} \\ \frac{di_{Gq}}{dt} = -\frac{r_S}{L_S} i_{Gq} - \omega i_{Gd} + \frac{1}{L_S} v_{Gq} - \frac{1}{L_S} v_{pccq} \\ \frac{dv_{pccd}}{dt} = \frac{1}{C_{pcc}} i_{gd} + \omega v_{pccq} + \frac{1}{C_{pcc}} i_{Gd} \\ \frac{dv_{pccq}}{dt} = \frac{1}{C_{pcc}} i_{gq} - \omega v_{pccd} + \frac{1}{C_{pcc}} i_{Gq} \end{cases} \tag{2}$$

The models of power converter in (1) and the grid in (2) are linearized at the operating point as

$$\Delta \dot{x}_{inv,i} = A_{inv,i} \Delta x_{inv,i} + B_{inv,i} C_G \Delta x_G \tag{3}$$

$$\Delta \dot{x}_G = A_G \Delta x_G + \sum_{i=1-n} B_G C_{inv,i} \Delta x_{inv,i} \tag{4}$$

where

$$\Delta x_{inv,i} = [\Delta i_{Lfd,i} \quad \Delta i_{Lfq,i} \quad \Delta v_{cfd,i} \quad \Delta v_{cfq,i} \\ \Delta i_{Lgd,i} \quad \Delta i_{Lgq,i} \quad \Delta X_{1d,i} \quad \Delta X_{1q,i} \ ]^T$$

$$\Delta x_G = \begin{bmatrix} \Delta v_{pccd} & \Delta v_{pccq} & \Delta i_{gd} & \Delta i_{gq} \end{bmatrix}^T$$

To provide a modular and scalable solution for a large-scale power electronics based power system, the CCM is employed for model connection of components. The overall small signal model of the system can be integrated using CCM. The small signal model of the grid connected three-inverter system is expressed as

$$A_s = \begin{bmatrix} A_{inv,A} & 0 & 0 & B_{inv,A} C_G \\ 0 & A_{inv,B} & 0 & B_{inv,B} C_G \\ 0 & 0 & A_{inv,C} & B_{inv,C} C_G \\ B_G C_{inv,A} & B_G C_{inv,B} & B_G C_{inv,C} & A_G \end{bmatrix} \tag{5}$$

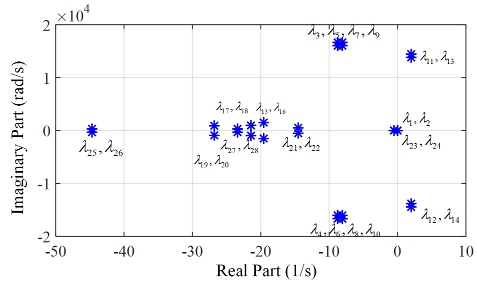

Fig. 4. Eigenvalue loci of the grid connected three-inverter system.

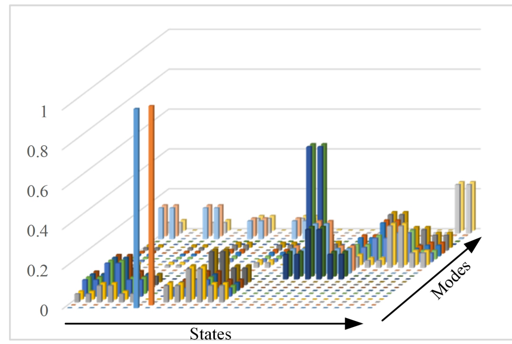

Fig. 5. Participation factor analysis for the grid connected three-inverter system.

2) Stability analysis: The linearized state-space model in (5) is analyzed by examining eigenvalues of the system matrix. Fig. 4 shows the eigenvalue plot for the system with the parameters in Table II. As can be obsered, there are poles in the right half plane, which means system is unstable. The modes λ_{11-14} are unstable modes.

As it is difficult to localize the instability root from the eigenvalue analysis in Fig. 5, the participation factor analysis is performed. The participation factor analysis calculates the contribution of each state to a certain mode to identify the states that have dominant effects on the dominant eigenvalues. The participation factors for the system are depicted in Fig. 5. The dominant states to the unstable modes λ_{11-14} are $i_{Lfd,C}$, $i_{Lfq,C}$, $i_{Cfd,C}$, $i_{Cfq,C}$, $i_{Lgd,C}$ and $i_{Lgq,C}$ with the participation factors 0.124, 0.124, 0.249, 0.249, 0.125 and 0.125, respectively. Therefore, Inverter C has a dominant impact on the unstable result.

Fig. 6 shows the eigenvalue loci with the variation of current control gain from 9 to 14. It reveals that when the gain is larger than 11, some eigenvalues move to the right half plane. Therefore, to ensure system stability, controller is selected as 10.

B. Impedance based method

1) Impedance modeling: The output admittance of ith inverter model with LCL filter Y_{oi} (i=A,B,C) can be obtained based on [19], as

$$Y_{oi,i} = \frac{Y_{o,i}(s)}{1 + G_{cgi}(s) G_{PWM}(s) Y_{gi,i}(s)} \tag{6}$$

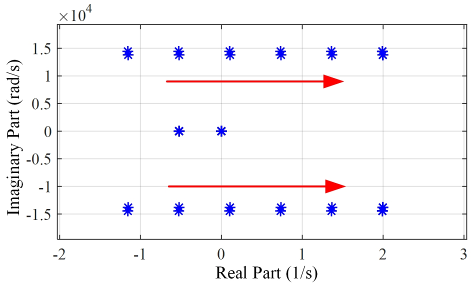

Fig. 6. Loci of the dominant eigenvalues with the variation of current control gain in Inverter C ($k_{cp,C} = 9 - 14$).

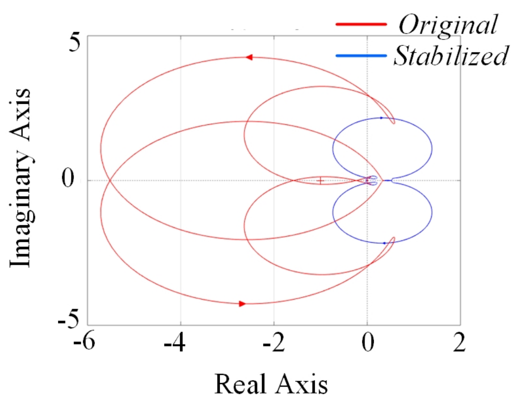

Fig. 7. Nyquist plot for the system with original parameter and redesigned parameter

where

$$Y_{gi,i}(s) = \frac{Z_{Cf,i}}{Z_{Cf,i}Z_{Lf,i} + Z_{Lg,i}Z_{Lf,i} + Z_{Cf,i}Z_{Lg,i}} \tag{7}$$

$$Y_{o,i}(s) = \frac{Z_{Cf,i} + Z_{Lf,i}}{Z_{Cf,i}Z_{Lf,i} + Z_{Lg,i}Z_{Lf,i} + Z_{Cf,i}Z_{Lg,i}} \tag{8}$$

$$G_{cgi}(s) = k_{cp,i} + \frac{k_{cr,i}s}{s^2 + \omega_1^2} \tag{9}$$

$$G_{PWM}(s) = e^{-1.5T_s s} \tag{10}$$

and grid admittance Y_g

$$Y_g = 1/(R_S + sL_S) \tag{11}$$

2) Stability analysis: Based on the stability issue to be studied, partitioning point can be selected. Here we study the integration of Inverter C to the grid connected inverter system with Inverters A+B as an example. So the Inverter C can be seen as the load side and the rest system is the source side, with the minor loop gain calculated as

$$T_{MLG} = Y_{oC}/(Y_g + Y_{oA} + Y_{oB}) \tag{12}$$

The red line in Fig. 7 depicts the Nyquist plot for the system with original parameters. It can be observed that Nyquist plot encircles (-1, 0j) point and thus, with the integration of Inverter C, the system is unstable.

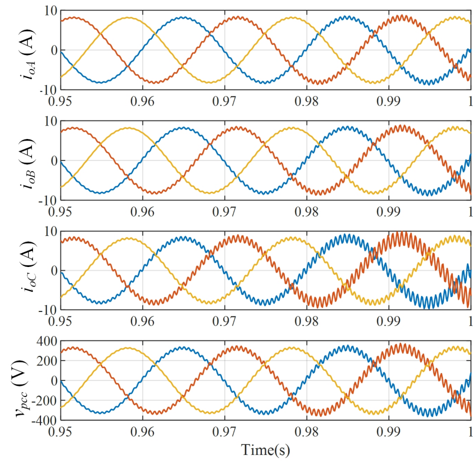

Fig. 8. Simulation results with original control parameter $k_{cp,C} = 12$.

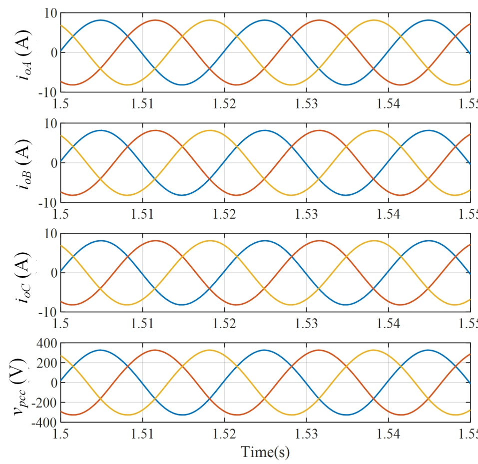

Fig. 9. Simulation results with redesigned control parameter $k_{cp,C} = 10$.

To stabilize system, the original proportional gain of the current controller in Converter C is redesigned so that the Nyquist plot will not encircle (-1, 0j) point. As can be seen in the blue line in Fig. 7, the system is stable with proportional gain redesigned as 10.

C. Simulation and experimental verification

1) Simulation verification: Fig. 8 demonstrates the simulation results of output currents of three inverters and the grid voltage with the original parameters in Table II. The results indicate that the system is unstable, which verifies the analytical results of eigenvalue method in Fig. 6 and impedance method in Fig. 7.

Fig. 9 presents the simulation results with the redesigned proportional gain in Inverter C, as suggested by Fig. 6 in eigenvalue method and Fig. 7 in impedance based method. The results of current dynamics and voltage dynamics present that the system is stable, which validates the analytical results.

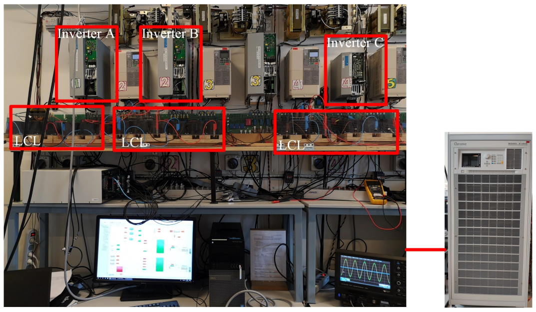

Fig. 10. Experimental platform

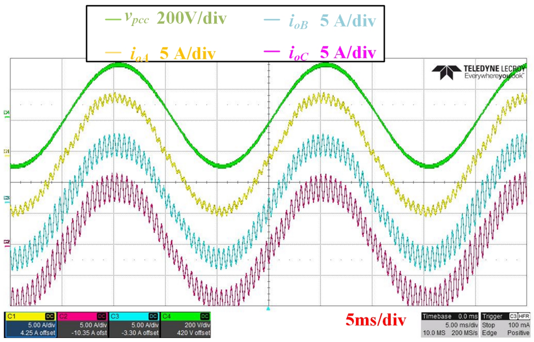

Fig. 11. Experimental results with original control parameter $k_{cp,C} = 12$.

2) Experimental verification: The laboratory platform of a grid connected multi-inverter system is established for further verification of the results, as shown in Fig. 10. Three inverters are integrated to the grid simulator though LCL filters and grid line inductor. The parameters are the same as that in Table II. The control algorithm is implemented in dSPACE 1007 to generate PWM signals for inverters.

The experimental results of the system with original parameter in Table II are shown in Fig. 11. The current response of three inverters and the voltage response at PCC show that the system is unstable, which verifies the analytical and simulation results.

Fig. 12 shows the experimental results with the redesigned current loop proportional gain of Inverter C at 10. System is stable, which validates the analytical and simulation results.

IV. Conclusion

This paper proposes a conceptual guideline for systematic stability analysis for power electronics based power system. Based on the system information available and the stability issue to be studied, the eigenvalue method or impedance based method is selected and detailed procedure is presented, including system modeling, stability analysis, system verification and mitigation. The selection criteria of the eigenvalue method and impedance based method are illustrated. A case study of a grid connected multi-inverter system is studied using eigenvalue method and impedance based method. The results are verified by simulation and experimental results. It shows that eigenvalue method is a good solution to find

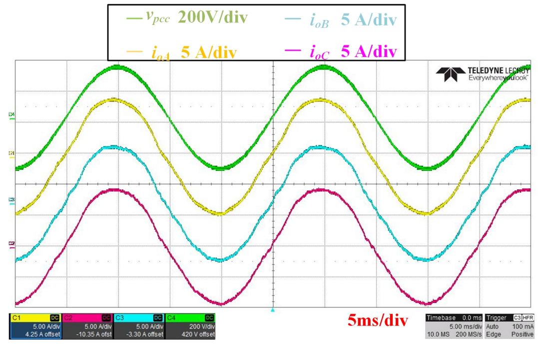

Fig. 12. Experimental results with redesigned control parameter $k_{cp,C} = 10$.

the unstable root of the overall system and design the stable parameters; while impedance method is suitable to investigate the interactions of two subsystems and the effect of a new subsystem integrated into the existing system.

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